



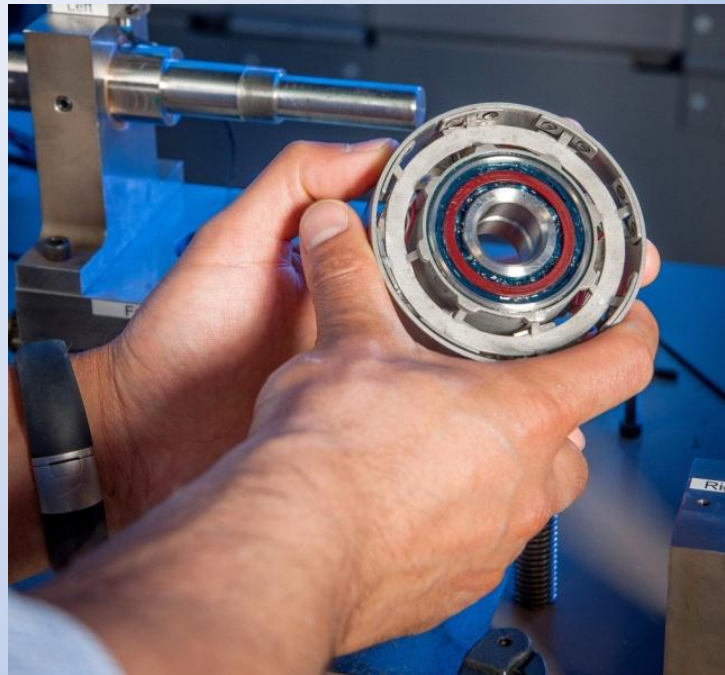
The Vibration Ring

– A global vibration and noise control solution for rotating machines

NASA Aeronautics Research Institute

NASA Glenn Research Center: Vivake Asnani (PI), Timothy Krantz, Damon Delap

Army Research Laboratory: LTC David Stringer



NASA Aeronautics Research Mission Directorate (ARMD)

FY12 Seedling Phase I Technical Seminar

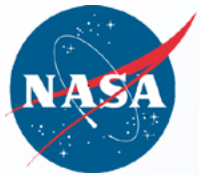
July 10, 2013



Outline

NASA Aeronautics Research Institute

- Motivation
- Concept
- Novel aspects of concept
- Potential impact
- Phase 1: Progress
- Phase 2: Proposed work
- Technology infusion plan



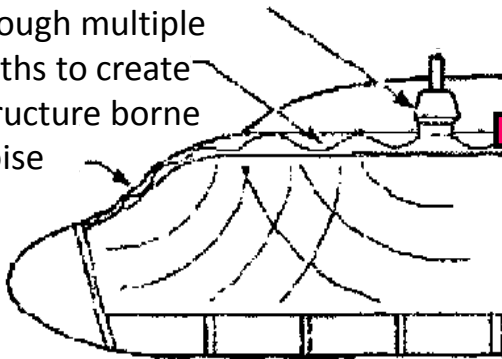
Motivation

NASA Aeronautics Research Institute



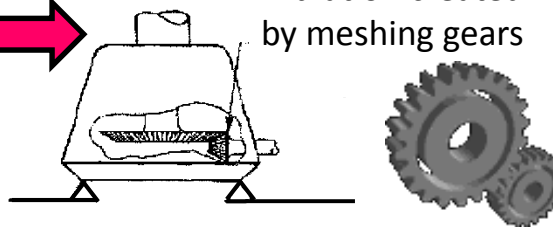
- Machines are the predominant source of noise in our society.
- Noise levels increase as machines become more powerful and lighter in weight.
- We were motivated the by extreme gear noise problem that exists in helicopters.
- Cabin noise exceeds 100 dB, making it impossible to communicate without headset.
- This environment prohibits widespread use of rotorcraft for civilian transportation.

Vibration travels through multiple paths to create structure borne noise



Gearbox attached to helicopter cabin

Vibration created by meshing gears



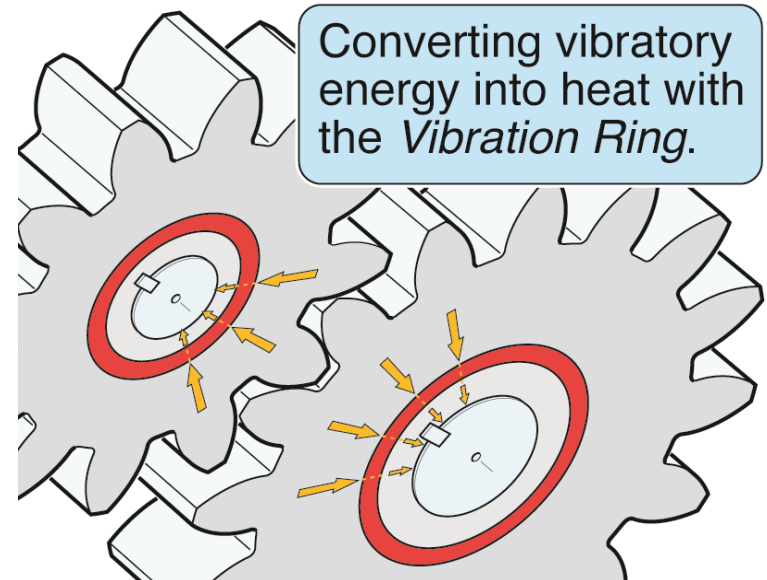


Concept

NASA Aeronautics Research Institute

The Vibration Ring

- Preventative noise control solution for rotating machines.
- Inserted between driveline components. E.g. Gears, bearings, shafts, fans, etc.
- Converts vibration into heat before it manifests as noise.
- We envision this as an off-the-shelf component available to any machine designer.





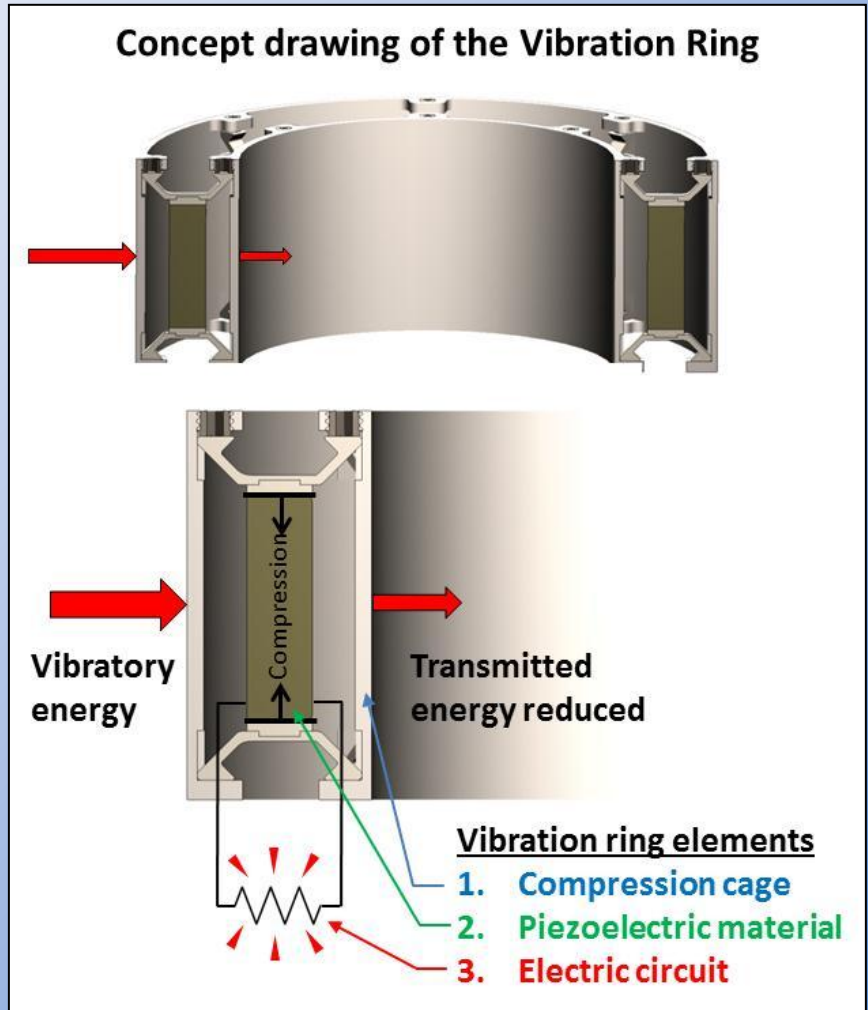
Novel aspects of concept

NASA Aeronautics Research Institute

- Unlike other damping treatments, the vibration ring is rigid and can be installed into a driveline.
- Provides an indirect damping effect by converting vibration into electricity and then into heat.

3 elements

- The **compression cage** is a metal annulus with mechanical amplifiers inside.
- The amplifiers compress the internal **piezoelectric material** when external vibratory force is applied.
- Compression of the piezoelectric material creates electric charge, which is converted to heat by the **electric circuit**.





Potential Impact

NASA Aeronautics Research Institute

Directly supports national aeronautics & NASA goals

- **National aeronautics security goal¹**: Reduce main rotor gearbox noise by 20dB.
 - Lesson pilot fatigue, enabling longer range and more frequency use of rotorcraft.
- **NASA's Rotary Wing project goal²**: Reduce cabin noise to less than 77 dB.
 - Improving rotorcraft passenger acceptant in civilian transportation.
- **National aeronautics safety goal³** to develop vehicle health monitoring systems.
 - Vibration ring has potential to provide power for driveline sensors.
- **Benefit to society**: Could be used in any rotating machine to prevent noise from being generated. (lawn mowers, automobiles, factory machines, etc.)

References

- 1) Security and Homeland Defense Goal #2, in the 2010 National Aeronautics Research and Development Plan, pp.28
- 2) Subsonic Rotary Wing Project goals, in the 2011 ARMD Program and Project overview, pp. 10.
- 3) Aviation and Safety R&D Goal #1, in the 2010 National Aeronautics Research and Development Plan, pp.36.



Phase 1: Goal and approach

NASA Aeronautics Research Institute

- Goal: Establish the feasibility of the Vibration Ring.
 - Develop a mechanism that performs the vibration energy conversion.
 - Practical in terms of fabrication, assembly, and installation.
- Approach
 - Analysis: Electro-mechanical modeling to create parametric design charts.
 - Design: Focus on creating the compression cage using the following tools.
 - Solid modeling: Checkout ideas for assembly
 - Finite element analysis: Verify analytical results. Examine deformation and stress.
 - Prototyping: Checkout manufacturing techniques, materials, and provide test articles.
 - Testing: Examine deformation and energy conversion performance using prototypes of the most promising designs.



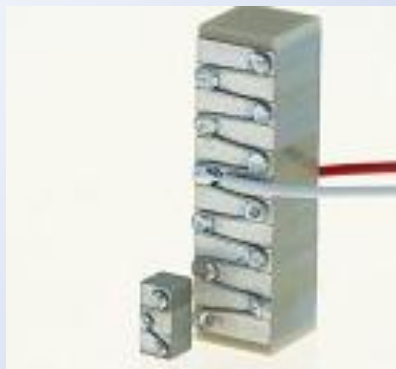
Phase 1: Analytical work

NASA Aeronautics Research Institute

Ring stacks

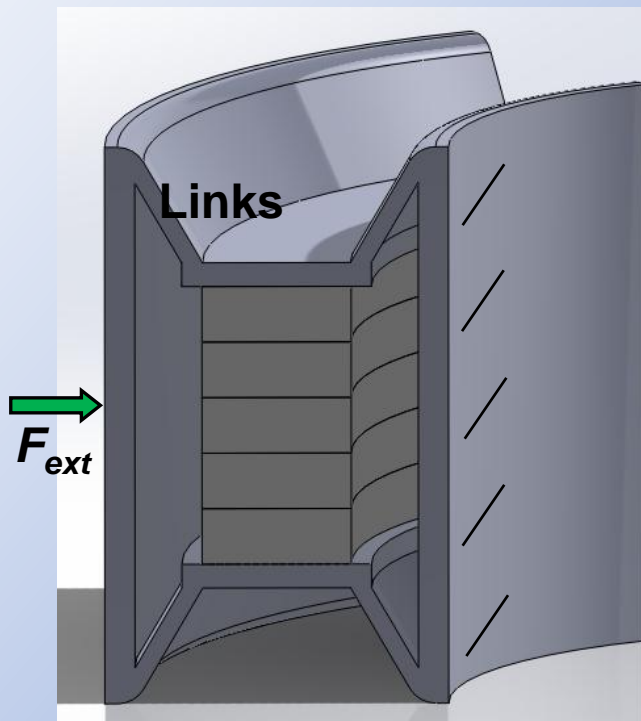


Plate stacks



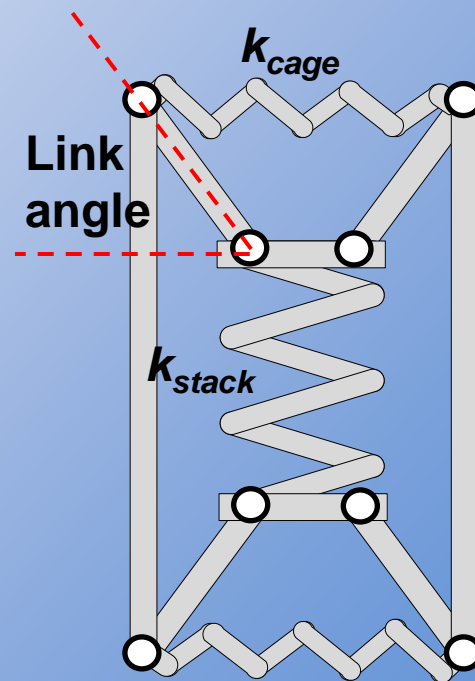
Picture from noliac.com

Vibration Ring cross-section



Links transfer force to piezoelectric stack

2D Mechanical model



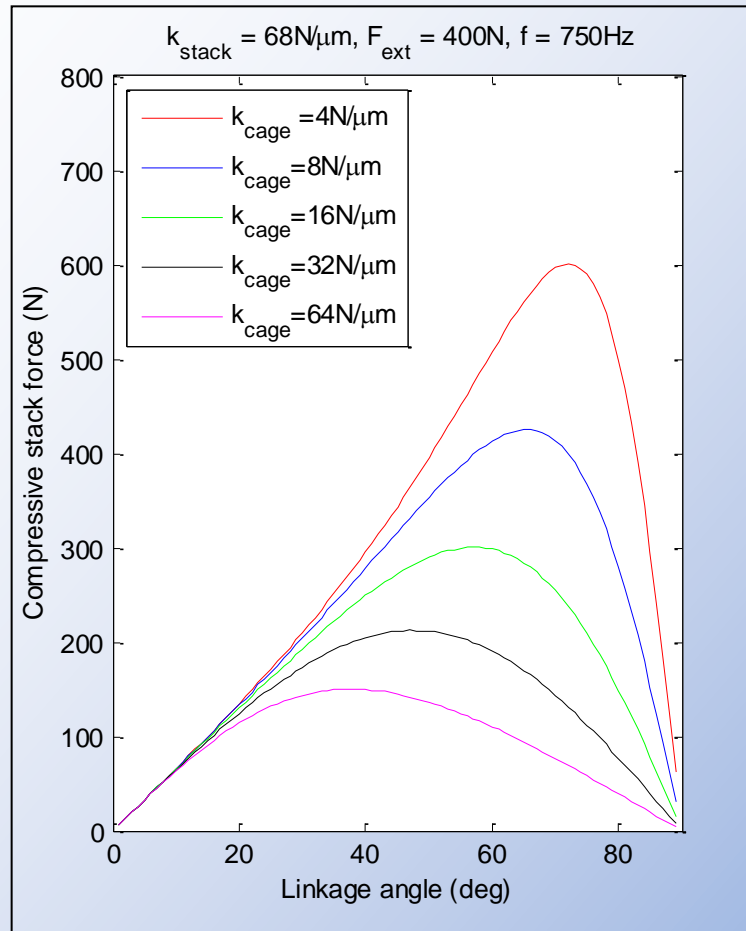
Link angle and cage stiffness control force transfer to stack



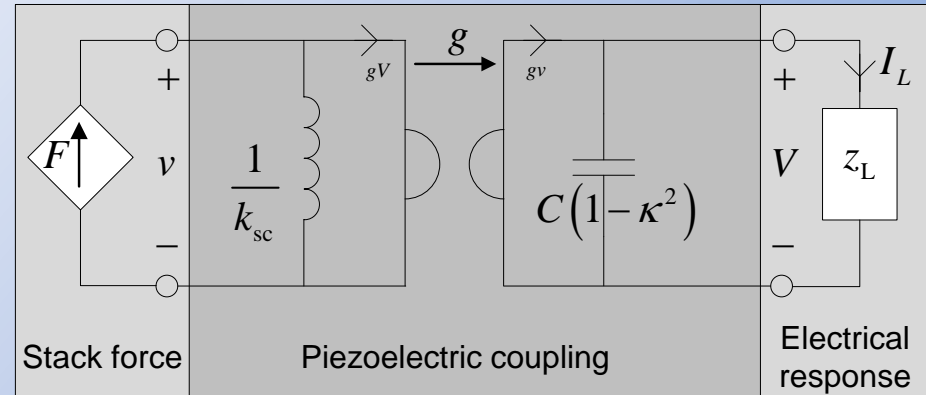
Phase 1: Analytical work

NASA Aeronautics Research Institute

Mechanical tuning

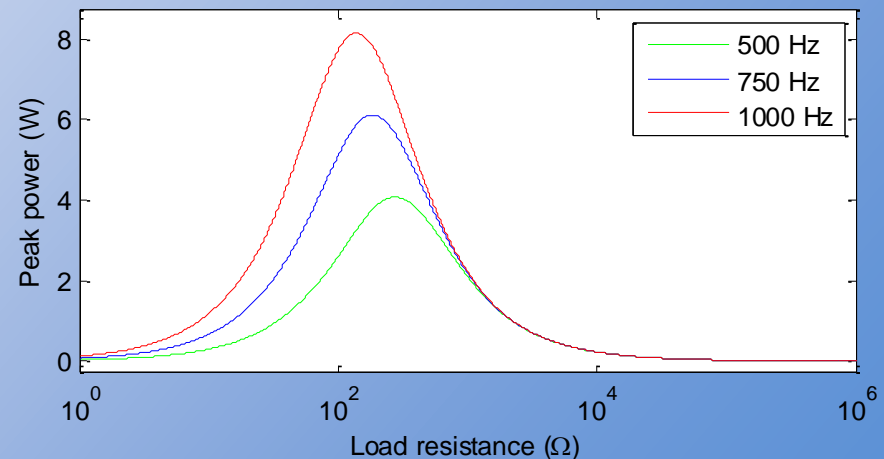


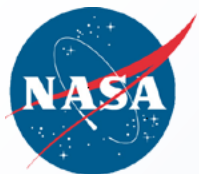
Stacks modeled as generators*



*Based on linear piezo equations (ANSI/IEEE Std. 176-1987)

Electrical tuning

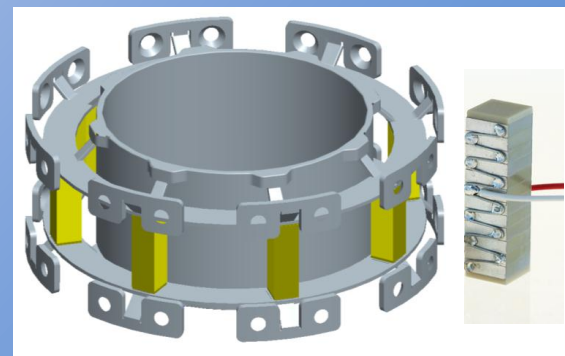
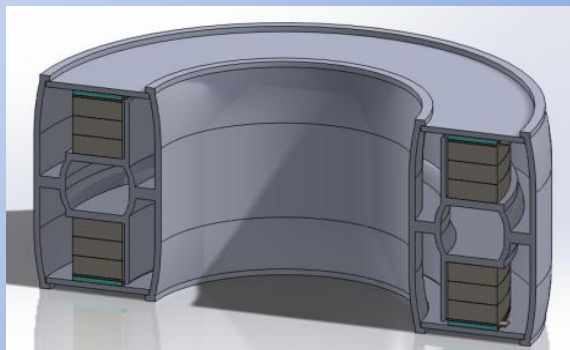
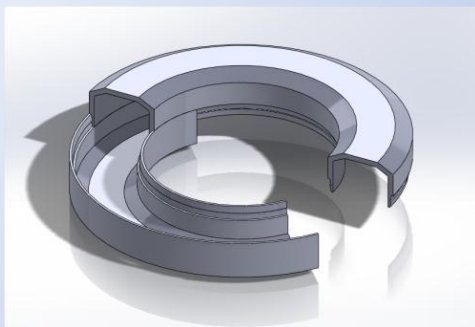
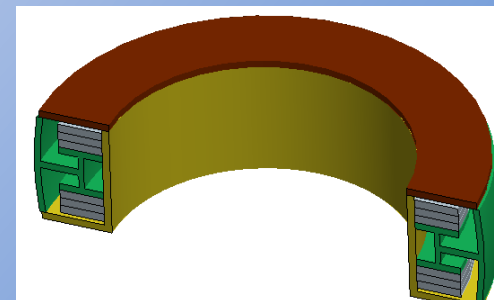
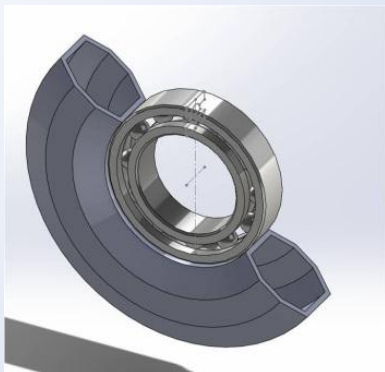
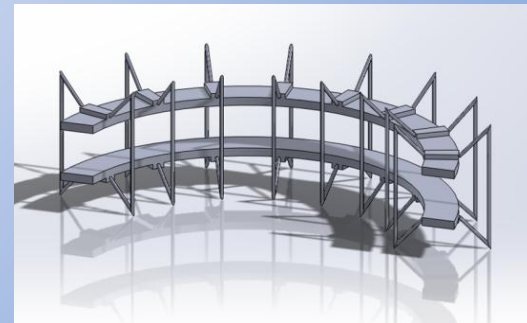
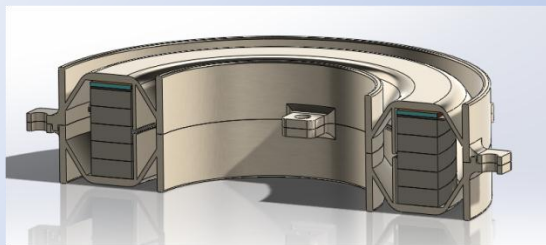




Phase 1: Design work

NASA Aeronautics Research Institute

Visual evolution of design concepts. In total 11 concepts were evaluated.
Concepts were evaluated using solid modeling, finite element analysis, and prototyping.

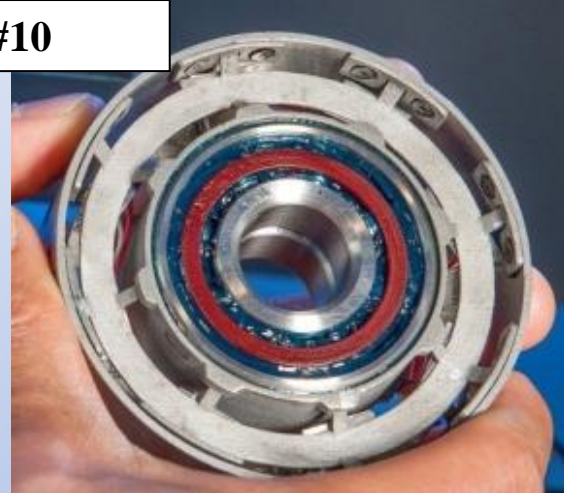
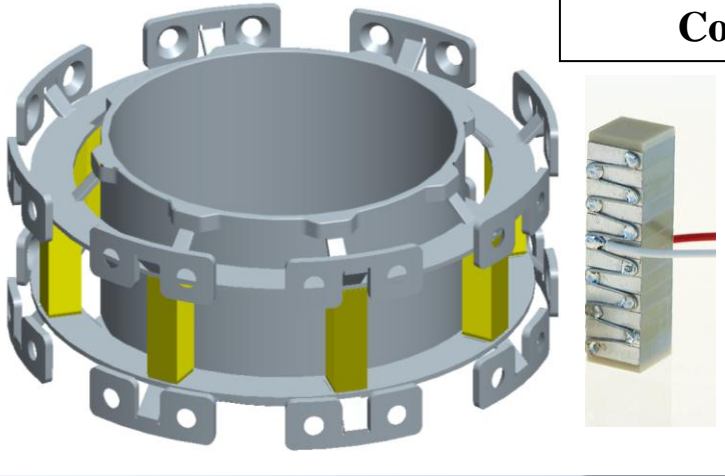




Phase 1: Design work

NASA Aeronautics Research Institute

Concept #10



Prototype made from powdered stainless steel

Strengths

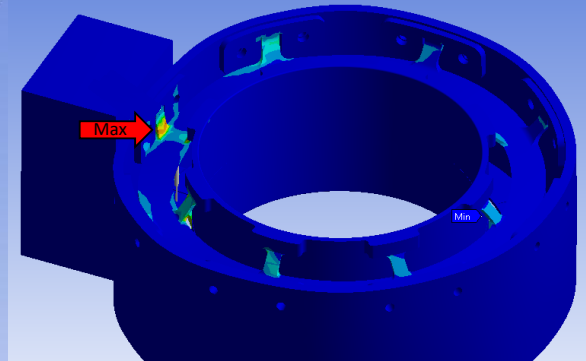
- Only 2 mechanical parts
- Simple/decoupled design
- FEA matches design charts from 2D model

Limitations

- Multiple piezoelectric stacks
- Additive manufacturing- laser sintering
- Difficult assembly, screws and shims
- FEA shows high sensitivity to link tolerances
- Sintering warped amplifier links.

Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
2/5/2013 5:14 PM

19049 Max
16932
14816
12699
10583
8466.2
6349.6
4233.1
2116.5
0.00093852 Min



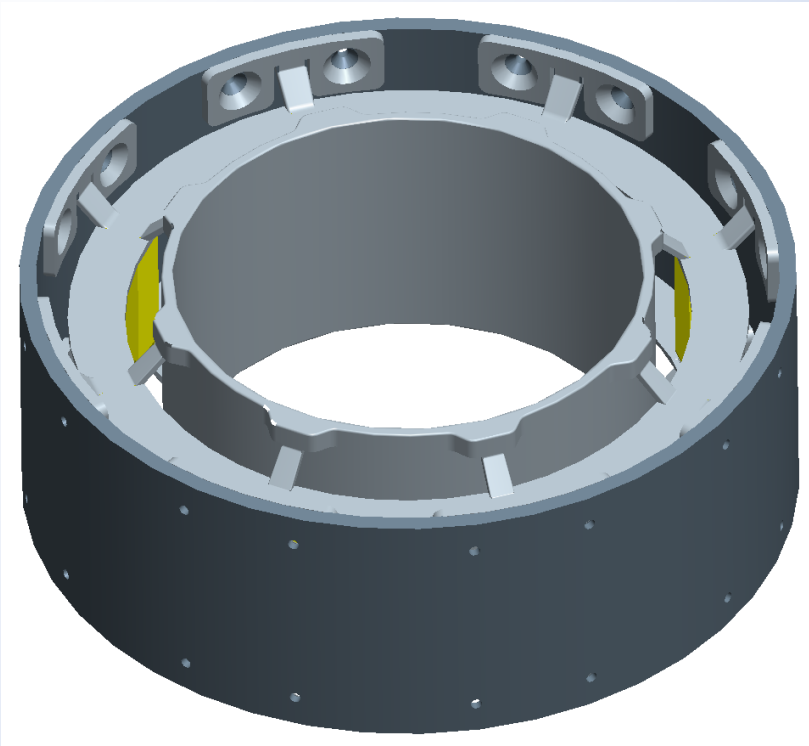
FEA evaluation of stiffness, stress, force transferred to stacks



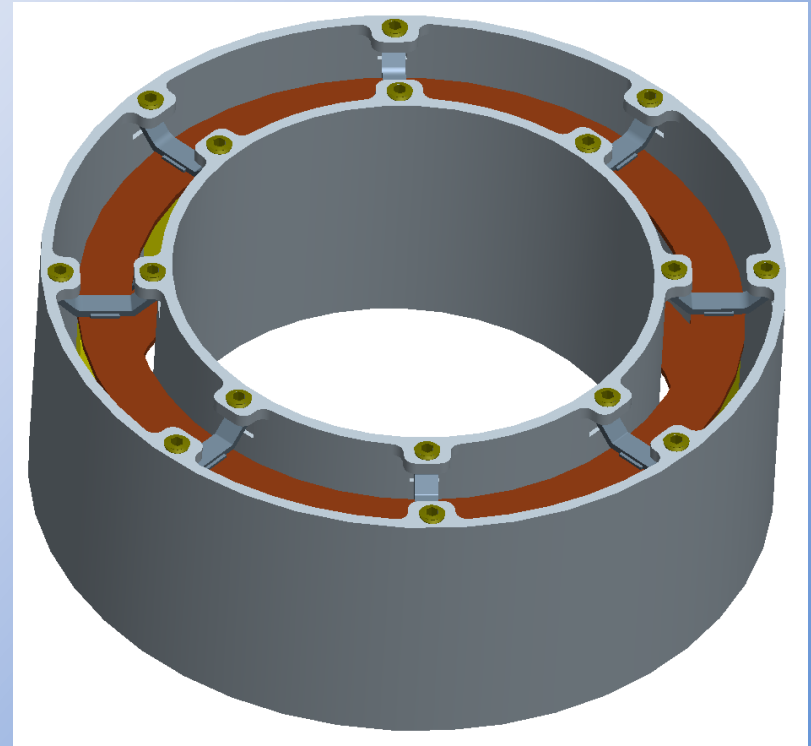
Phase 1: Design work

NASA Aeronautics Research Institute

Concept 10



Concept 11



Notes about Concept 11

- Same theoretical performance, but improved manufacturing / assembly.
- Links cut precisely using wire electrical discharge manufacturing. Avoids warping.
- Easy assembly, no shims (see next slide).

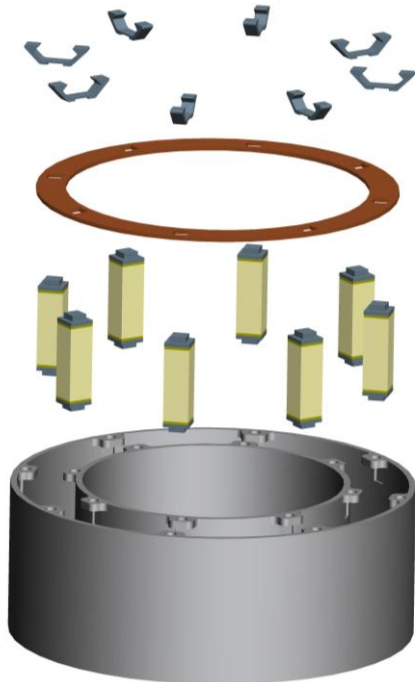


Phase 1: Design Work

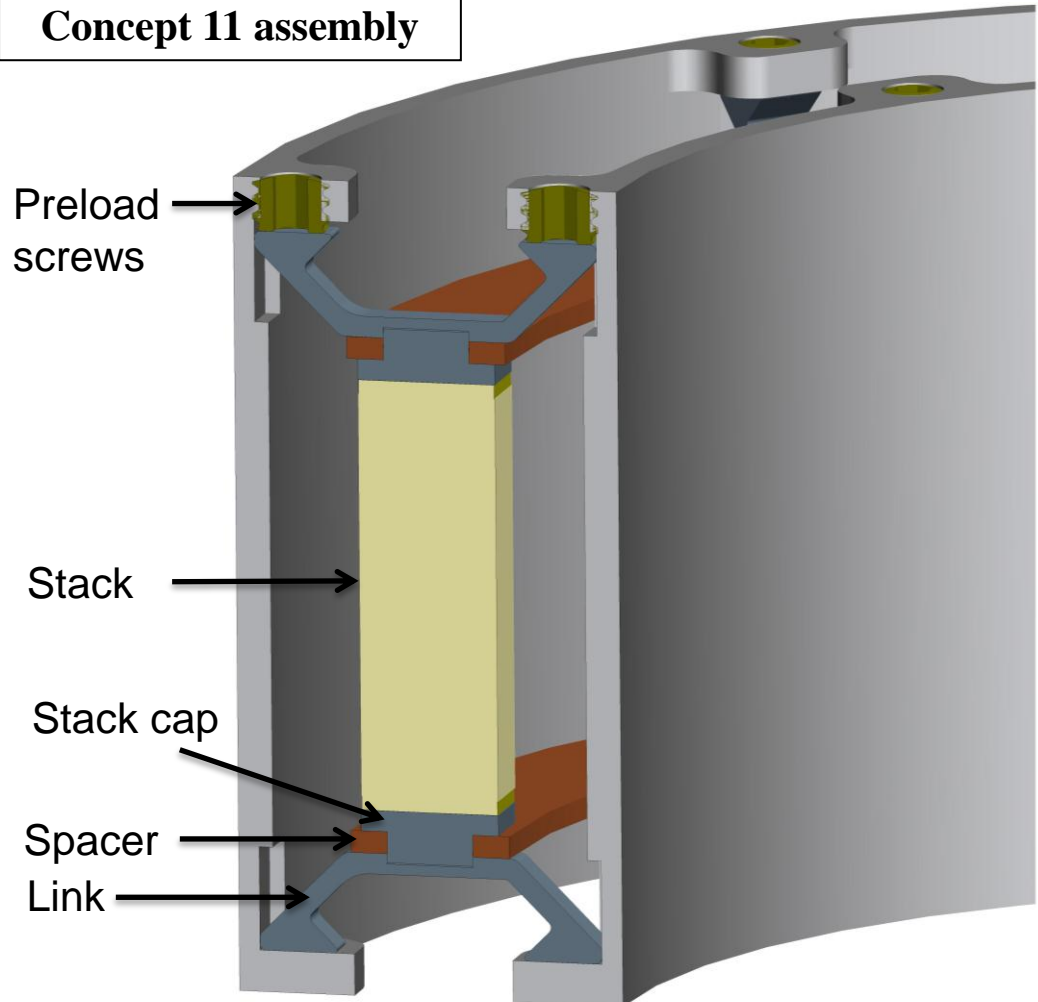
NASA Aeronautics Research Institute

Concept 11 parts

- More parts than concept 10
- No additive manufacturing
- Less uncertainty in dimensions



Concept 11 assembly

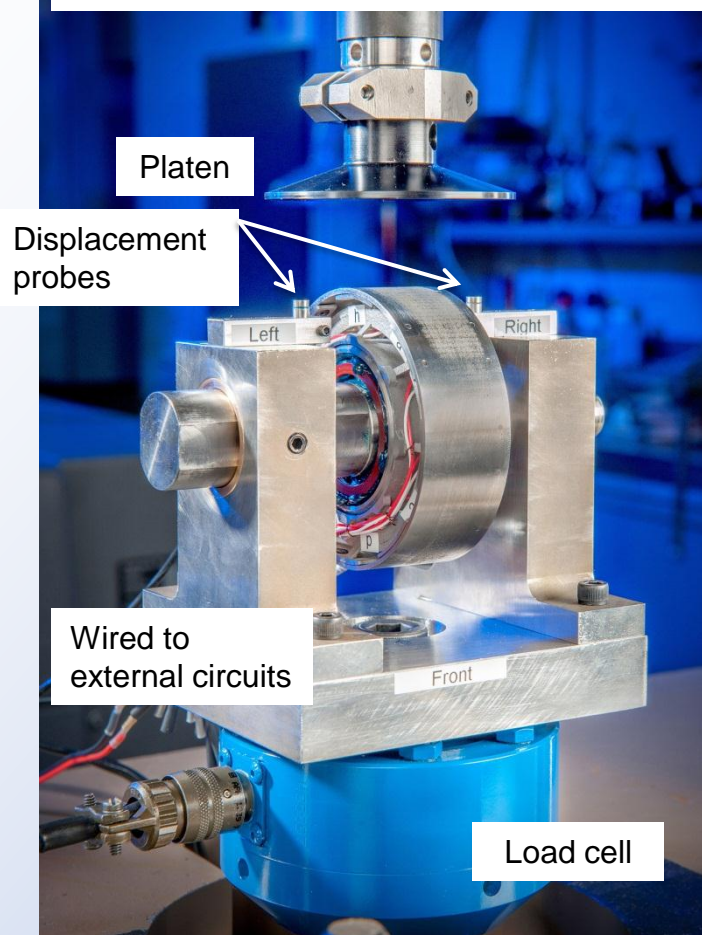




Phase 1: Testing

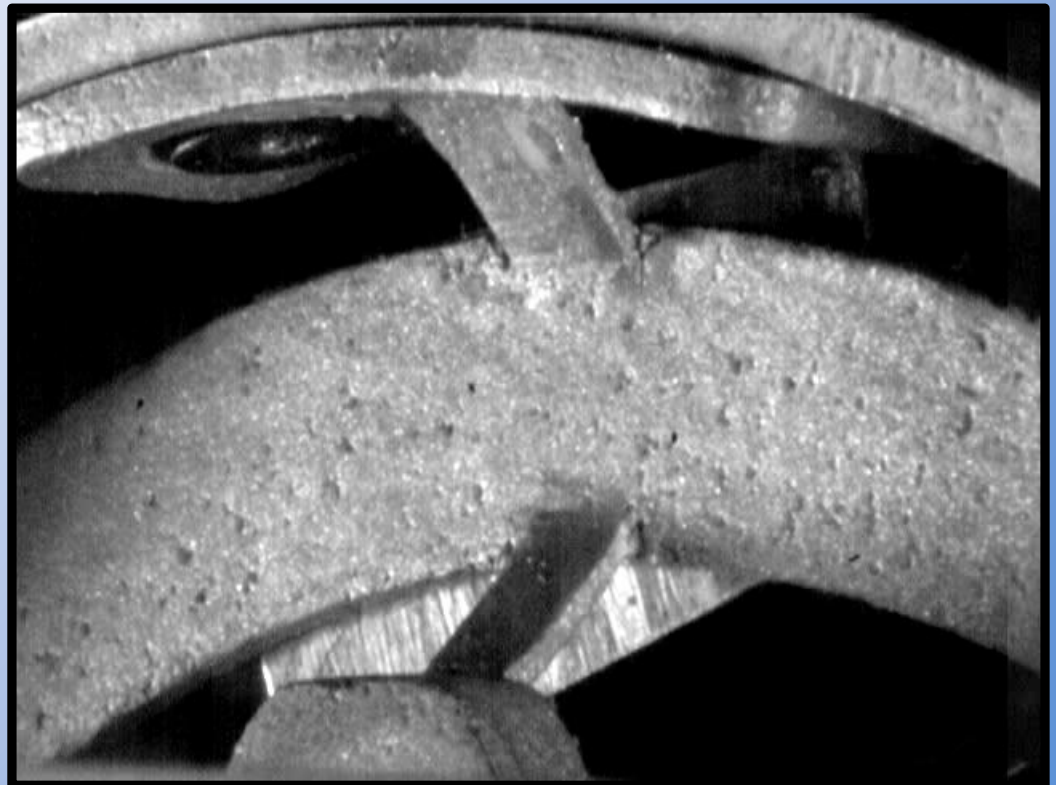
NASA Aeronautics Research Institute

Energy conversion testing



Concept 10 load frame testing

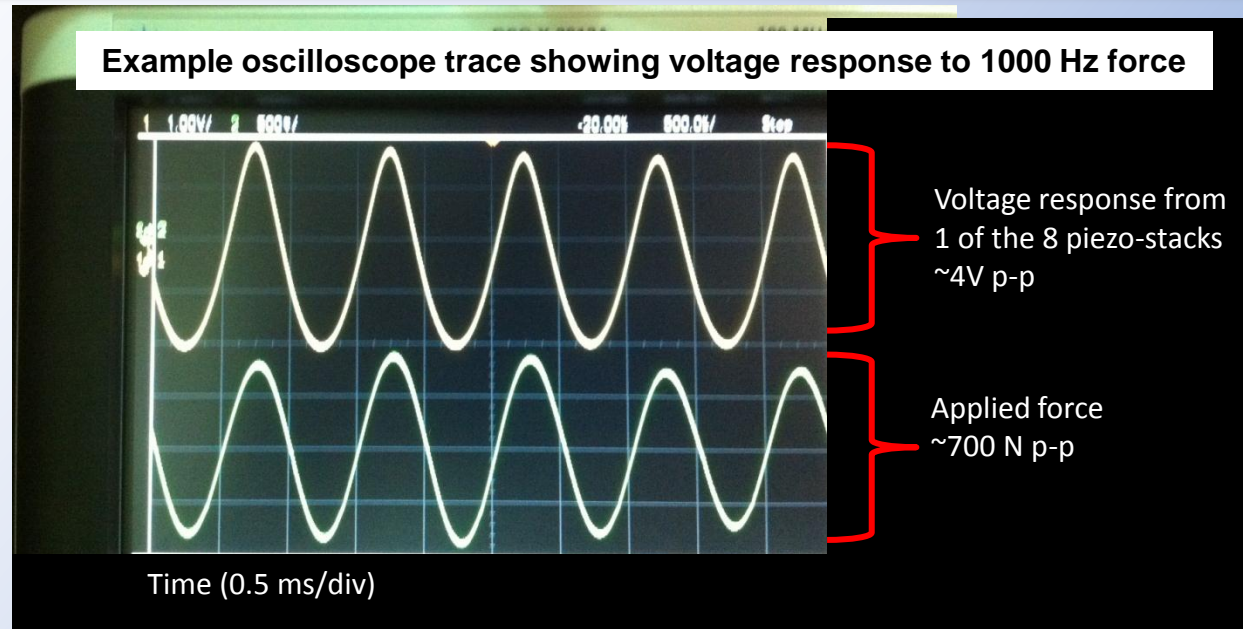
- Deformation much greater than expected
- Took high speed video for troubleshooting
- Hypothesize that links are flexing





Phase 1: Testing

NASA Aeronautics Research Institute



- Testing verified that load voltage is proportional to applied force; however,
 - Deformation: Expected micrometer range, observed >100 micrometers
 - Power: Expected 1000 mW range, observed < 50 mW
- Suspect deviations in manufacturing; links are flexing, less force transferred to stacks.
 - Video analysis will help identify unexpected motions
 - Concept 11 (improved manufacturing) will be tested for comparison
- Full matrix of energy conversion and deformation data being collected



Phase 2: Objectives

NASA Aeronautics Research Institute

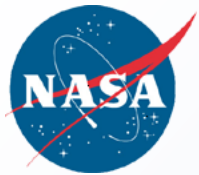
1. Maximize the energy conversion rate from vibration to heat
 - Less concept iterations, focus on finding the performance potential
2. Evaluate vibration and noise reduction in an actual driveline.
 - A driveline gearbox will be modified to include vibration rings, and their effect on vibration and noise will be measured.



Phase 2: Maximize energy conversion

NASA Aeronautics Research Institute

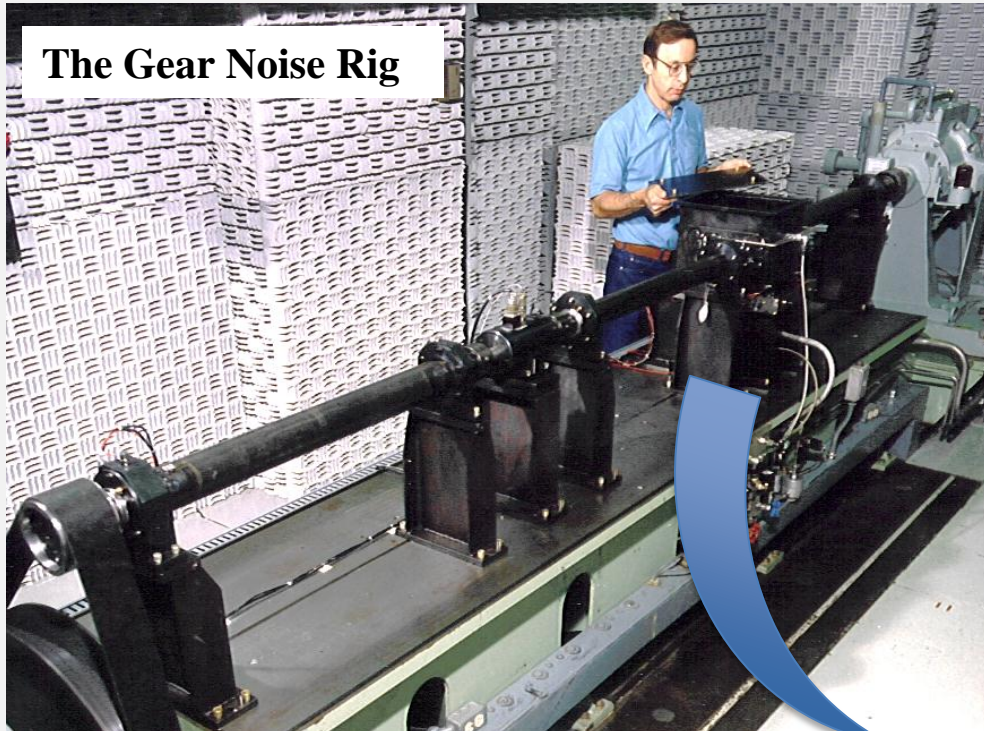
- **Mechanical design:** Using the modeling tools created in phase 1, the link angle and stiffness variables will be tuned for maximize transfer of force to the piezoelectric material.
- **Manufacturing:** In phase 1, FEA revealed that performance is sensitive to variations in compression cage geometry. Therefore precision manufacturing will be used to maintain design integrity.
- **Piezoelectric material:** Current materials can convert 35% of applied mechanical energy. Will use single-crystal materials capable of 50% conversion. Load testing will be done to make the material selection.
- **Electric circuit:** Thus far only resistive circuits were used, providing broad-band energy consumption. Reactive circuits will be used to create resonance, amplifying energy consumption in frequency bands.



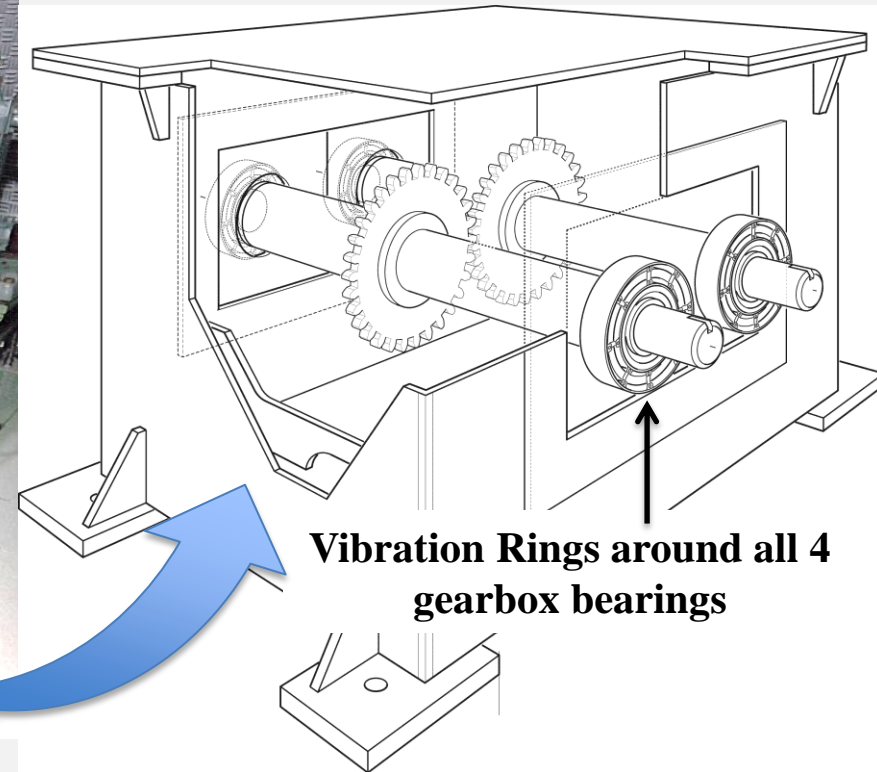
Phase 2: Evaluate noise reduction

NASA Aeronautics Research Institute

The Gear Noise Rig

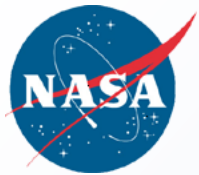


Driveline system inside of an acoustically treated room



Vibration Rings around all 4 gearbox bearings

- Gearbox vibration and noise measurements will be taken and analyzed at the gear mesh frequencies.
- Success criteria: 20% (2 dB) noise reduction will be considered successful, while 30% (3 dB) will be considered outstanding.



Phase 2: Supplementary task

NASA Aeronautics Research Institute

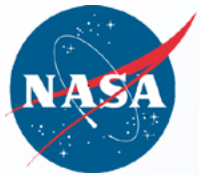
- The purpose is to engage the Ohio State University (OSU) / take advantage of their expertise in smart materials to improve the Vibration Ring.
- Research support would be provided for 1 graduate student, including an internship at NASA GRC.
- Objective 1: Identify / test alternative smart materials to improve the energy conversion performance and versatility of the vibration ring.
 - Deliverable: Structural and energy conversion data on candidate materials
- Objective 2: To develop alternative Vibration Ring design concepts, taking advantage of 'structural' smart materials
 - Deliverable: Functional prototype
- Success criteria: New concept simplifies design (e.g. eliminates need for compression cage); enables vibration energy conversion from multiple directions; expands potential applications.



Technology infusion plan

NASA Aeronautics Research Institute

- **Private sector:** Collaborate with the Smart Vehicle Concept (SVC) Center. This is a Nation Science Foundation sponsored research center, led by OSU, with members from academia, government, and industry. The SVC has focus to apply smart material technology to vehicles.
 - Briefing of the project at SVC meetings, twice annually
 - Funded project carried out by OSU
 - Hosting an OSU student for summer internship assignment
- **NASA:** The Rotary Wing project would like to incorporate the Vibration Ring as a part of their rotorcraft technology development portfolio. We have been and will continue to provide them with monthly updates.
- **US Army:** The Army Research Laboratory has expressed interested in continued collaboration beyond phase 2. Co-investigator LTC Stringer will serve as liaison.
- **Establish a collaborative research project with the interested parties before the end of phase 2.**



Phase 1: Summary of accomplishments

NASA Aeronautics Research Institute

- **Analysis**
 - Hybrid models were created to represent the Vibration Ring as a dynamic system.
 - Mechanical aspects of the model were verified against FEA.
 - Parametric charts were made for optimizing energy conversion.
- **Design**
 - The design was evolved through 11 concepts, evaluating assembly, manufacturing, and materials.
 - A total of 6 prototypes were created in the process.
- **Testing**
 - A load testing system was setup to validate predictions and evaluate performance.
 - Load testing was implemented on the concept 10 prototype, verifying that vibration energy is being partially dissipated by the circuit.
 - Performance limitations of concept 10 were revealed, and troubleshooting is being done to understand the causes.
 - Before project end, a full matrix of energy conversion performance data will be collected.
- Phase 1 showed that that its feasible to convert driveline vibration energy to heat using a Vibration Ring mechanism that is practical to build and assemble.



Phase 2: Summary of proposed work

NASA Aeronautics Research Institute

Main task

1. Maximize the energy conversion rate from vibration to heat
 - Less concept iterations; focus on finding the energy conversion potential
2. Evaluate vibration and noise reduction in an actual driveline
 - Prove the utility, if the Vibration Ring provides global vibration and noise reduction in a driveline

Supplementary task

1. Identify / test alternative materials
 - New materials are expected to spark innovative changes in the design
2. Develop alternative design concepts, taking advantage of structural materials.
 - Expect that 'structural' materials will simplify the design, possibly merging the individual parts into a combined structure.

Technology Infusion Plan

1. Engage the private sector through the OSU led Smart Vehicle Concept Center
2. Collaborate with NASA's Rotary Wing project and the Army Research Laboratory.
3. Establish a collaborative research project with the interested parties before the end of phase 2.